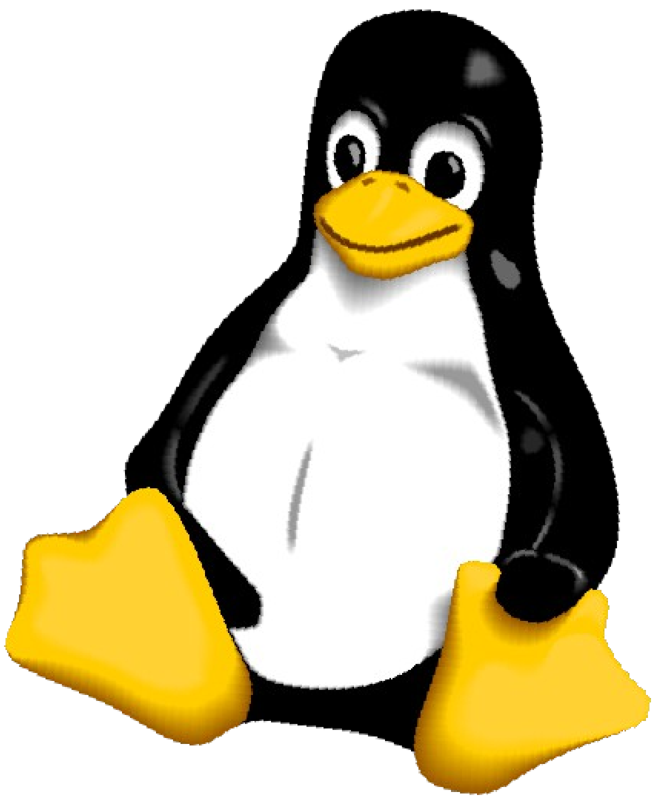
USB and the Real World



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Embedded Linux Conference

April 28, 2014

About the Presenter

- Chief Bit-Banger at **Signal 11 Software**
  - Products and **consulting services**
- **Linux Kernel**
- **Firmware**
- **Userspace**
- **Training**
- **USB**
  - **M-Stack** USB Device Stack for PIC
- **802.15.4** wireless

USB Overview

USB Bus Speeds

- **Low** Speed
  - 1.5 Mb/sec
- **Full** Speed
  - 12 Mb/sec
- **High** Speed
  - 480 Mb/sec
- **Super** Speed
  - 5.0 Gb/sec

USB Bus Speeds

- Bus speeds are the **rate of bit transmission** on the bus
- Bus speeds are **NOT** data transfer speeds
- USB protocol can have **significant overhead**
- USB overhead **can be mitigated** if your protocol is designed correctly.

USB Standards

- USB **1.1** – 1998
  - Low Speed / Full Speed
- USB **2.0** – 2000
  - High Speed added
- USB **3.0** – 2008
  - SuperSpeed added
- USB Standards **do NOT imply** a bus speed!
  - *A **USB 2.0** device can be High Speed, Full Speed, or Low Speed*

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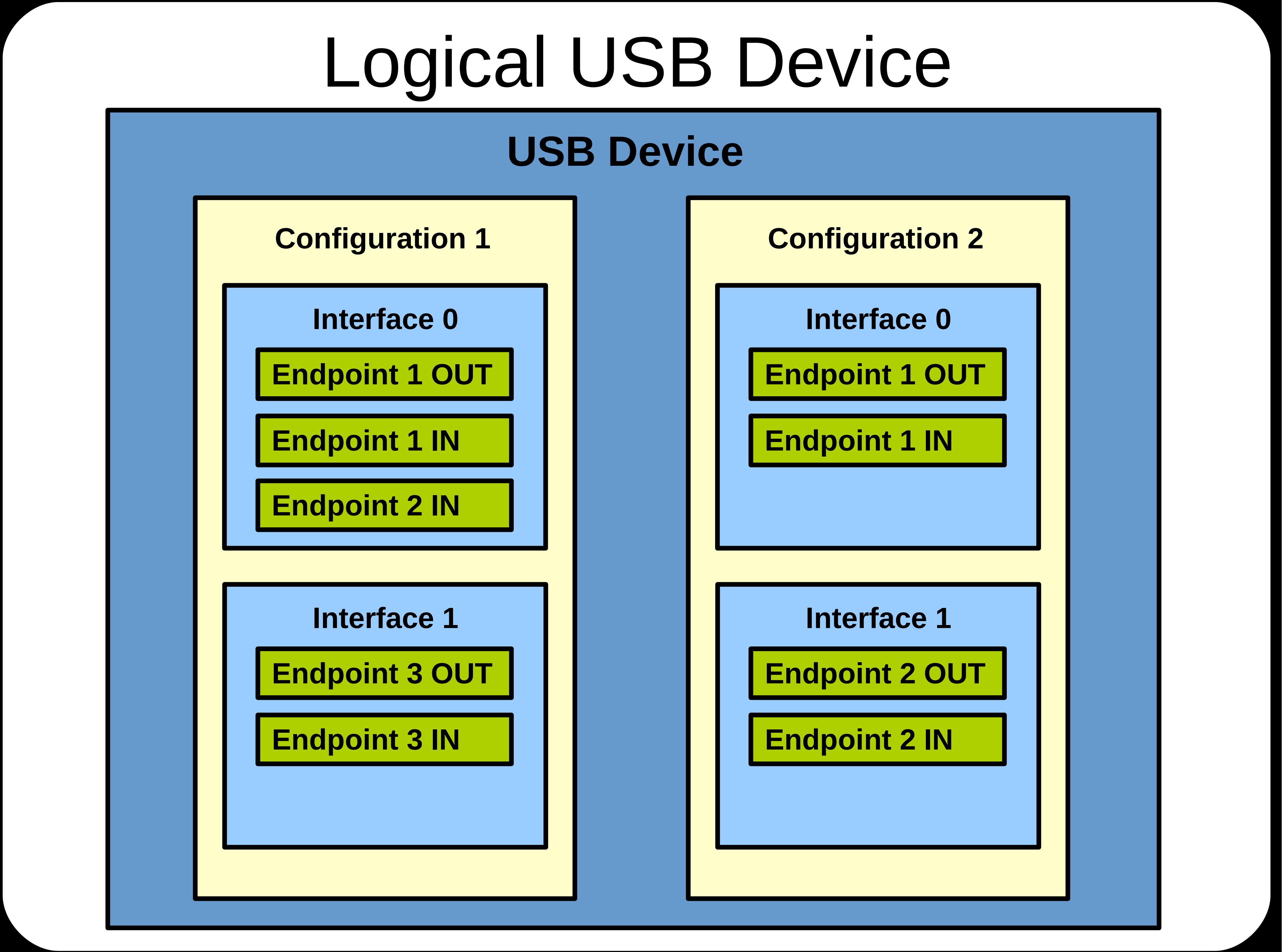
USB Terminology

- **Device** – Logical or physical entity which performs a function.
  - Thumb drive, joystick, etc.
- **Configuration** – A mode in which to operate.
  - Many devices have one configuration.
  - Only one configuration is active at a time.

USB Terminology

- **Interface** – A related set of Endpoints which present a single feature or function to the host.
  - A configuration may have **multiple** interfaces
  - All interfaces in a configuration are **active at the same time**.
- **Endpoint** – A source or sink of data
  - Interfaces often contain **multiple endpoints**, each active all the time.


Logical USB Device
USB Device
Configuration 1
Interface 0
Endpoint 1 OUT
Endpoint 1 IN
Endpoint 2 IN
Interface 1
Endpoint 3 OUT
Endpoint 3 IN
Configuration 2
Interface 0
Endpoint 1 OUT
Endpoint 1 IN
Interface 1
Endpoint 2 OUT
Endpoint 2 IN

Endpoints

- Four types of Endpoints
  - **Control**
    - **Bi-directional** endpoint
      - Status stage can return success/failure
    - **Multi-stage** transfers
    - Used for **enumeration**
    - Can be used for application

Endpoints

- **Interrupt**
  - Transfers a **small amount** of **low-latency** data
  - Reserves bandwidth on the bus
  - Used for **time-sensitive** data (HID).
- **Bulk**
  - Used for **large** data transfers
  - Used for large, **time-insensitive** data (Network packets, Mass Storage, etc).
  - Does not reserve bandwidth on bus
    - Uses whatever time is left over

Endpoints

- **Isochronous**
  - Transfers a **large amount** of **time-sensitive** data
  - Delivery is **not guaranteed**
    - **No ACKs are sent**
  - Used for Audio and Video streams
    - Late data is as good as no data
    - Better to drop a frame than to delay and force a re-transmission

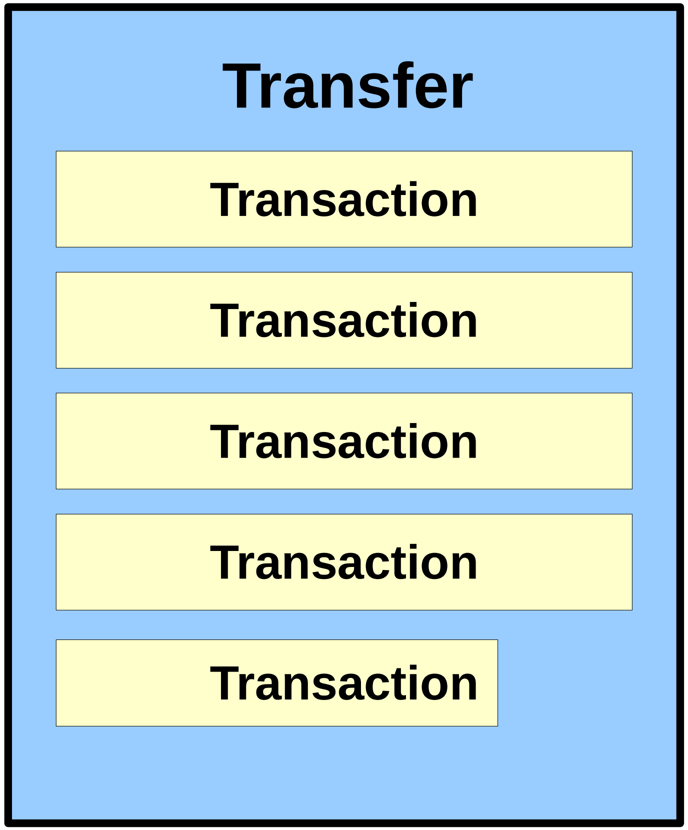
Endpoints

- **Endpoint Length**
  - The **maximum amount of data** an endpoint can support sending or receiving **per transaction**.
  - Max endpoint sizes:
    - Full-speed:
      - Bulk/Interrupt: **64**
      - Isoc: **1024**
    - High-Speed:
      - Bulk: **512**
      - Interrupt: **3072**
      - Isoc: **1024 x3**

Transfers

- **Transaction**
  - Delivery of service to an endpoint
  - Max data size: **Endpoint length**
- **Transfer**
  - **One or more** transactions moving information between host and device.
  - ➢ *Transfers can be large, even on small endpoints!*

Transfers



- Transfers contain **one or more transactions.**
- Transfers are ended by:
  - A **short transaction**
    OR
  - When the **desired amount of data** has been transferred
    - *As requested by the host*

Terminology

- In/Out
  - In USB parlance, the terms **In** and **Out** indicate direction from the **Host** perspective.
    - **Out**: Host to Device
    - **In**: Device to Host

The Bus

- USB is a **Host-controlled** bus
  - Nothing on the bus happens without the host first initiating it.
  - Devices cannot initiate a transaction.
  - The USB is a **Polled Bus**
  - The Host polls each device, requesting data or sending data.

Transactions

- **IN** Transaction (Device to Host)
  - Host sends an **IN token**
  - If the device has data:
    - Device sends data
    - Host sends **ACK**

    else
    - Device sends **NAK**
  - ➢ *If the device sends a **NAK**,the host will retry repeatedly until timeout.*

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Transactions

- **OUT** Transaction (Host to Device)
  - Host sends an **OUT token**
  - Host sends the data (up to endpoint length)
  - Device sends an **ACK** (or **NAK**).

➢ *The data is sent before the host has a chance to respond at all.*

➢ *In the case of a **NAK**, the host will **retry** until timeout or success.*

Transactions

- All Transactions are initiated by the **Host**
- In **user space**, this is done from **libusb**:
  - Synchronous:

    ```
    libusb_control_transfer()
    libusb_bulk_transfer()
    libusb_interrupt_transfer()
    ```

  - Asynchronous:

    ```
    libusb_submit_transfer()
    ```

Transactions

- In **kernel space**, this is done from:
  - Synchronous:

    ```
    usb_control_msg()
    usb_bulk_msg()
    usb_interrupt_msg()
    ```

  - Asynchronous:

    ```
    usb_submit_urb()
    ```

Transactions

- For All types of Endpoint:
  - The Host **will not send** any IN or OUT tokens on the bus unless a **transfer is active**.
  - The bus is **idle** otherwise
  - Create and submit a transfer using the functions on the preceding slides.

Linux USB Gadget Interface and Hardware

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USB Gadget Interface

- Linux supports **USB Device Controllers** (UDC) through the **Gadget** framework.
  - Kernel sources in `drivers/usb/gadget/`
- The gadget framework is transitioning to use **configfs** for its configuration
  - See Matt Porter's presentation:
    - ***Kernel USB Gadget Configfs Interface***
    - Thursday, May 1 at 4:00 PM

USB Device Hardware

- UDC hardware is not standardized
  - This is different from most host controllers
  - We will focus on **musb, EG20T**, and **PIC32**
  - **musb**
    - – IP core by Mentor Graphics
      - Recently becoming usable
    - – Common on ARM SoC's such as the AM335x on the **BeagleBone Black** (**BBB**)
    - – Host and Device

USB Device Hardware

- **Intel EG20T Platform Controller Hub (PCH)**
  - Common on Intel-based x86 embedded platforms
  - Part of many industrial System-on-Module (SoM) parts
  - Device Only (EHCI typically used for Host)
- **Microchip PIC32MX**
  - Microcontroller
  - Does not run Linux (firmware solution)
  - Full-speed only
  - **M-Stack** OSS USB Stack

Test Hardware

Test Hardware

- **BeagleBone Black**
  - Texas Instruments / CircuitCo
  - AM3359, ARM Cortex-A8 SOC
  - 3.3v I/O, 0.1” spaced connectors
  - Boots mainline kernel and u-boot!
  - Ethernet, USB host and device (musb), Micro SD
  - Great for breadboard prototypes
  - http://www.beagleboard.org

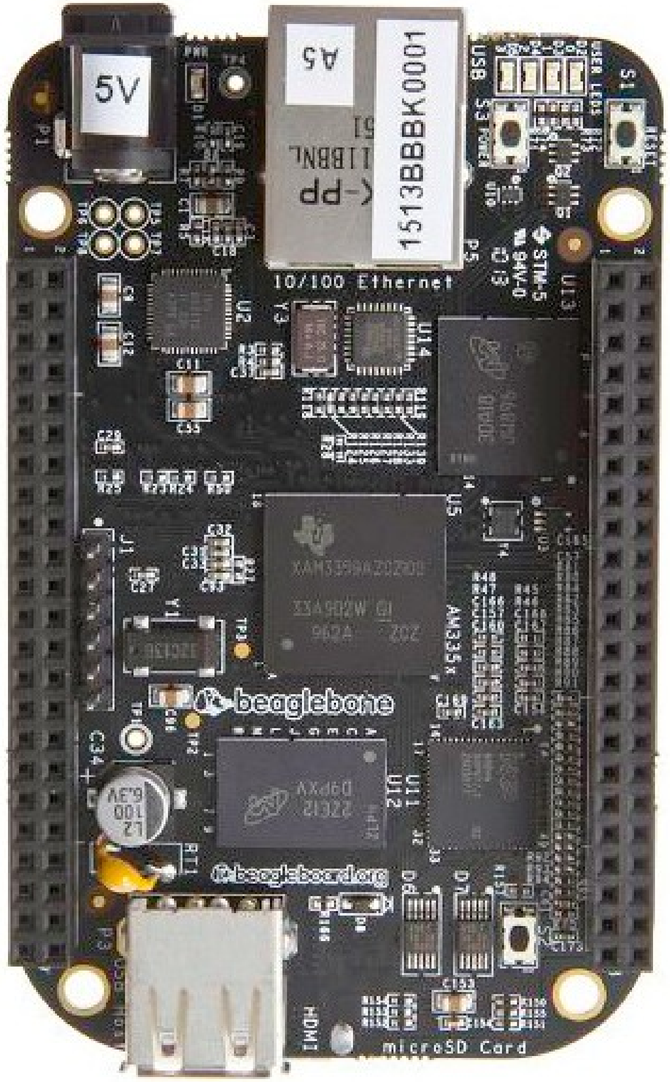


Image from beagleboard.org

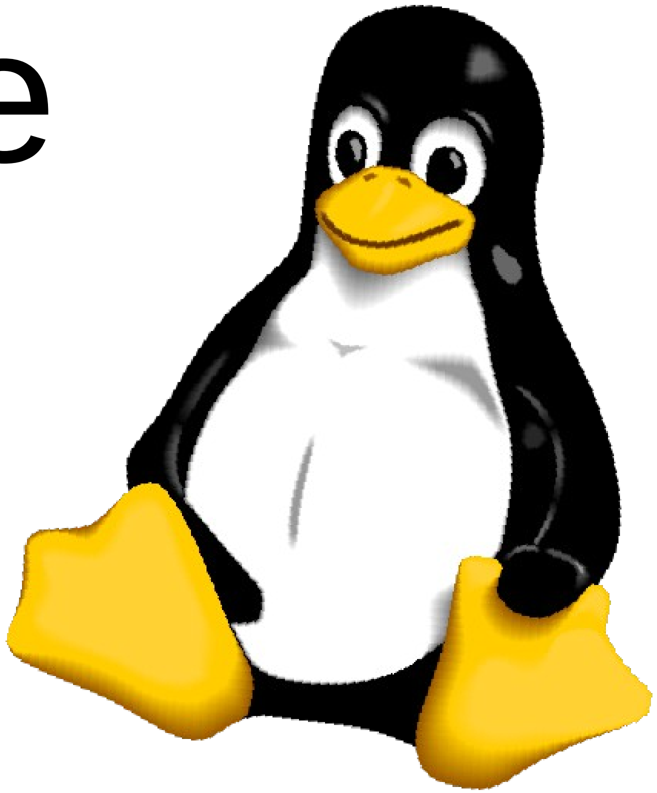
Test Hardware

- OEM **Intel Atom**-based board
  - Intel Atom E680
  - 1.6 GHz x86 hyperthreaded 32-bit CPU
  - 1 GB RAM
  - Intel **EG20T** platform controller
    - Supports USB Device (pch_udc driver)
    - Serial, CAN, Ethernet, more...

Test Hardware

- **ChipKit Max32**
  - PIC32MX795F512L
    - 32-bit Microcontroller
    - Up to 80 MHz (PLL)
      - Running at 60 MHz here
    - Full Speed USB
      - **M-Stack** OSS USB Stack
    - 512 kB flash
    - 128 kB RAM
    - Serial, CAN, Ethernet, SPI, I2C, A/D, RTCC
    - http://chipkit.net

Performance



Performance

- Three classes of USB device:
  1. Designer wants an **easy, well-supported connection** to a PC
  2. Designer wants to make use of an **existing device class** and not write drivers
  3. Designer wants #1 but also wants to **move a lot of data** quickly.

Performance

- For Cases #1 and #2, naïve methods can get the job done:
  - HID
  - Simplistic software on both the host and device side
    - For #2, **no software** on the host side!
  - Synchronous interfaces copied from examples

Performance

- A simple example:
  - High-speed Device
  - 512-byte bulk endpoints
  - **Receive** data from device using **libusb** in logical application-defined blocks
    - In this case let's use **64-bytes**

Simple Example - Host

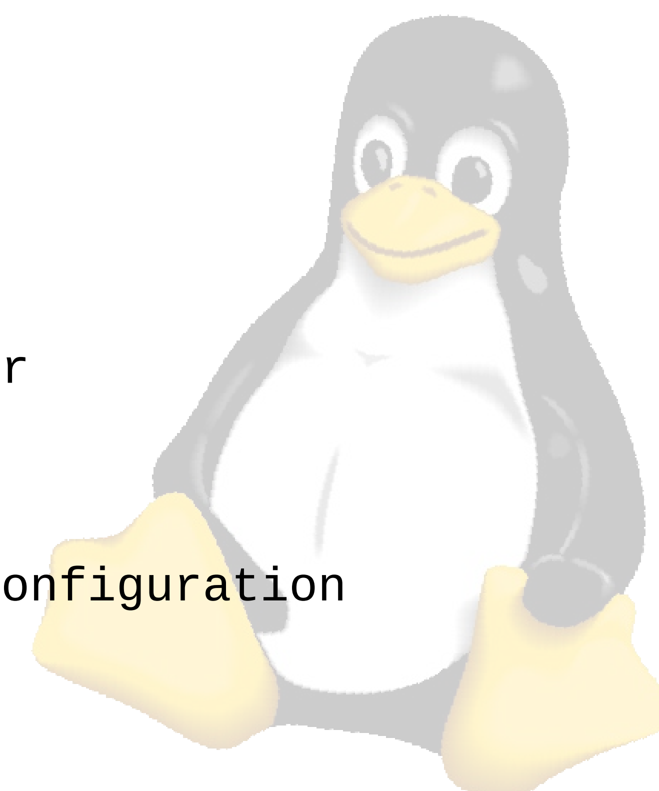
```c
unsigned char buf[64];
int actual_length;

do {
    /* Receive data from the device */
    res = libusb_bulk_transfer(handle, 0x81, buf,
              sizeof(buf), &actual_length, 100000);
    if (res < 0) {
        fprintf(stderr, "bulk transfer (in): %s\n",
                libusb_error_name(res));
        return 1;
    }
} while (res >= 0);
```

Simple Example - Device

```
#!/bin/sh -ex

# Setup the device (configfs)
modprobe libcomposite
mkdir -p config
mount none config -t configfs
cd config/usb_gadget/
mkdir g1
cd g1
echo 0x1a0a >idVendor
echo 0xbadd >idProduct
mkdir strings/0x409
echo 12345 >strings/0x409/serialnumber
echo "Signal 11" >strings/0x409/manufacturer
echo "Test" >strings/0x409/product
mkdir configs/c.1
mkdir configs/c.1/strings/0x409
echo "Config1" >configs/c.1/strings/0x409/configuration
```



Simple Example – Device (cont'd)

```
# Setup functionfs
mkdir functions/ffs.usb0
ln -s functions/ffs.usb0 configs/c.1

cd ../../../
mkdir -p ffs
mount usb0 ffs -t functionfs
cd ffs
../ffs-test 64 & # from the Linux kernel, with mods!
sleep 3
cd ..

# Enable the USB device
echo musb-hdrc.0.auto >config/usb_gadget/g1/UDC
```

- *Again, see **Matt Porter**'s presentation for exact steps regarding **configfs** and gadgets.*

Simple Example - Results

- On the BeagleBone Black:
  - Previous example will transfer at **4 Mbit/sec** !
  - Remember this is a high-speed device!
  - Clearly far too slow!
  - What can be done?

Performance Enhancements

- The simple example used libusb's **synchronous API**.
  - Good for **infrequent**, **single** transfers.
    - Easy to use, blocking, return code
  - Bad for any kind of **performance-critical** applications.
    - Why? Remember the nature of the USB bus....

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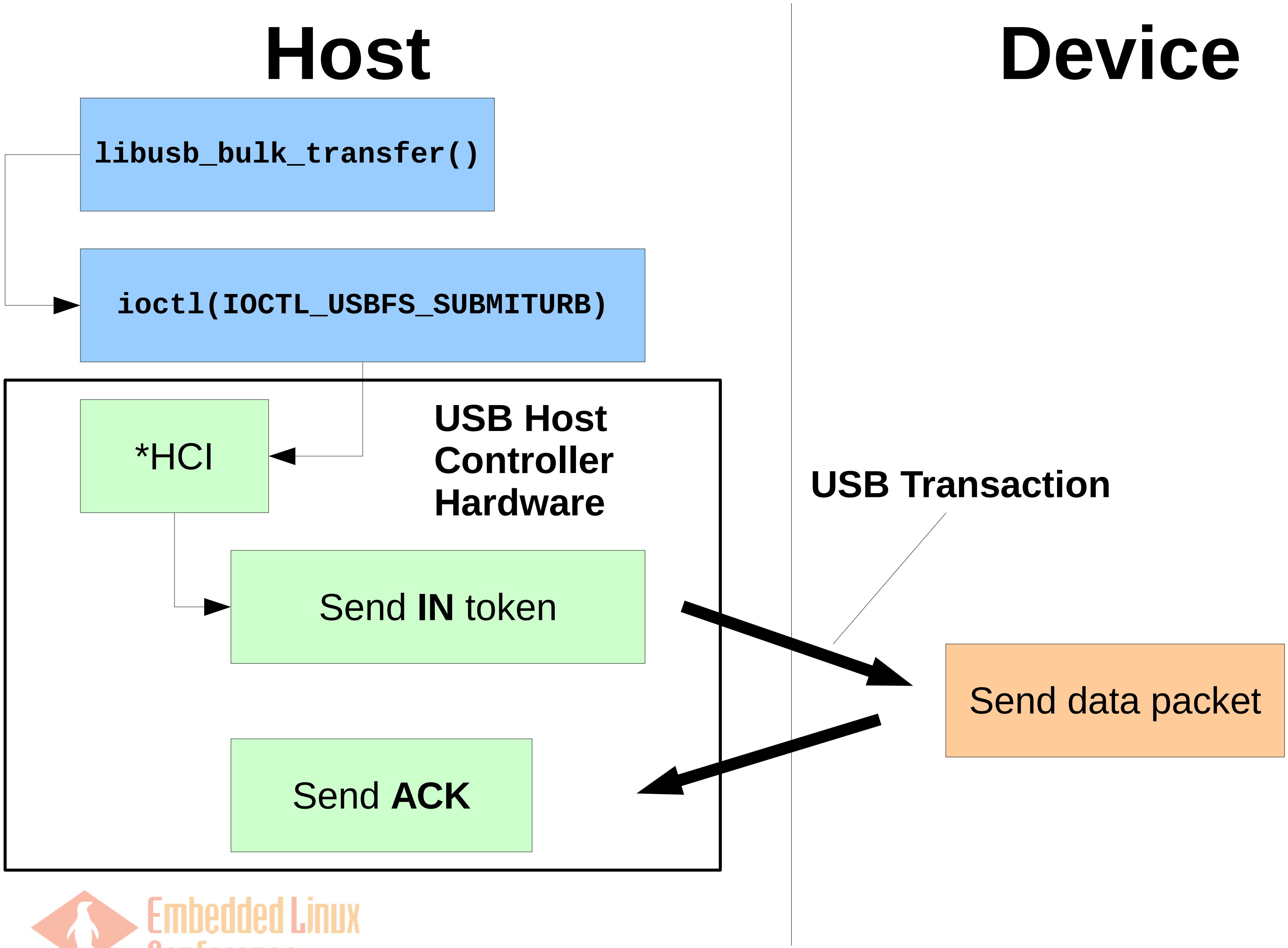
Synchronous API Issues

- The USB Bus
  - Entirely host controlled
  - Device only sends data when the host specifically **asks** for it.
  - The host controller will only ask for data when a **transfer is active**.
    - libusb **creates a transfer** when (in our example) `libusb_bulk_transfer()` is called.

Synchronous API Issues



Synchronous API Issues

- USB Bus
  - After a transfer completes, the device **will not send any more data** until another transfer is created and submitted!
  - In our simple example, this is done with `libusb_bulk_transfer()` in a **tight loop**.
    - Tight loops are **not tight enough**!
      - For short transfers time spent in software will be more than time spent in hardware!
      - All time spent in software is time a **transfer is not active**!

Asynchronous API

- Fortunately libusb and the kernel provide an **asynchronous API**.
  - Create **multiple** transfer objects
  - **Submit** transfer objects to the kernel
  - Receive **callback** when transfers complete
- When a transfer completes, there is another (submitted) transfer already queued.
  - **No downtime** between transfers!

Better Example - Host

```
static struct libusb_transfer
*create_transfer(libusb_device_handle *handle, size_t length) {
        struct libusb_transfer *transfer;
        unsigned char *buf;

        /* Set up the transfer object. */
        buf = malloc(length);
        transfer = libusb_alloc_transfer(0);
        libusb_fill_bulk_transfer(transfer,
                handle,
                0x81 /*ep*/,
                buf,
                length,
                read_callback,
                NULL/*cb data*/,
                5000/*timeout*/);

        return transfer;
}
```

Better Example – Host (cont'd)

```c
static void read_callback(struct libusb_transfer *transfer)
{
        int res;

        if (transfer->status == LIBUSB_TRANSFER_COMPLETED) {
                /* Success! Handle data received */
        }
        else {
                printf("Error: %d\n", transfer->status);
        }

        /* Re-submit the transfer object. */
        res = libusb_submit_transfer(transfer);
        if (res != 0) {
                printf("submitting. error code: %d\n", res);
        }
}
```

Better Example – Host (cont'd)

```
/* Create Transfers */
for (i = 0; i < 32; i++) {
        struct libusb_transfer *transfer =
                create_transfer(handle, buflen);
        libusb_submit_transfer(transfer);
}

/* Handle Events */
while (1) {
        res = libusb_handle_events(usb_context);
        if (res < 0) {
                printf("handle_events()error # %d\n",
                       res);

                /* Break out of this loop only on fatal error.*/
                if (res != LIBUSB_ERROR_BUSY &&
                    res != LIBUSB_ERROR_TIMEOUT &&
                    res != LIBUSB_ERROR_OVERFLOW &&
                    res != LIBUSB_ERROR_INTERRUPTED) {
                        break;
                }
        }
}
```

Asynchronous API

- This example creates and queues **32 transfers**.
- When a transfer completes, the completed transfer object is **re-queued**.
- All the transfers in the queue can conceivably complete **without a trip to userspace**.
- Results on BeagleBone Black:
  - **15 Mbit/sec**
    - A little better, but still not good!

Transfer Size

- The previous examples used a **64-byte** transfer size.
  - One short transaction per transfer
- The max bulk endpoint size is **512-bytes**.
- Larger transactions mean less overhead.
  - Each transaction requires three packets
    - **Token** phase
    - **Data** phase
    - **Handshake** phase (ACK/NAK)
  - Longer data packets means fewer transactions.

Transfer Size

- Results:
  - On BeagleBone Black, 512-byte transfers using the asynchronous API yields:
    - **82 Mbit/sec**
  - Better, but still sub-optimal
  - Why still so slow?
    - Transaction size is maximal...
    - Host side latency is minimal...
    - Use Analyzer to find out.

USB Analyzer

- TotalPhase Beagle Analyzers
  - Beagle USB 480 Power Protocol Analyzer
  - Well supported on Linux
  - Class-level debugging
  - Power (current/voltage) analysis
  - http://www.totalphase.com

USB Analyzer

~55 uSec per transaction

269962	1:51.484.971	512 B	05	01	IN txn [33 POLL]
269967	1:51.485.059	83 ns			[1 SOF]
269968	1:51.485.020	512 B	05	01	IN txn [25 POLL]
269973	1:51.485.075	512 B	05	01	IN txn [34 POLL]
269978	1:51.485.124	512 B	05	01	IN txn [34 POLL]
269983	1:51.485.184	83 ns			[1 SOF]
269984	1:51.485.186	512 B	05	01	IN txn [19 POLL]
269989	1:51.485.219	512 B	05	01	IN txn [34 POLL]
269994	1:51.485.309	83 ns			[1 SOF]
269995	1:51.485.268	512 B	05	01	IN txn [27 POLL]
270000	1:51.485.324	512 B	05	01	IN txn [34 POLL]
270005	1:51.485.374	512 B	05	01	IN txn [34 POLL]
270010	1:51.485.434	83 ns			[1 SOF]
270011	1:51.485.436	512 B	05	01	IN txn [21 POLL]
270016	1:51.485.472	512 B	05	01	IN txn [33 POLL]
270021	1:51.485.559	66 ns			[1 SOF]
270022	1:51.485.520	512 B	05	01	IN txn [25 POLL]
270027	1:51.485.574	512 B	05	01	IN txn [34 POLL]
270032	1:51.485.623	512 B	05	01	IN txn [34 POLL]
270037	1:51.485.684	66 ns			[1 SOF]
270038	1:51.485.686	512 B	05	01	IN txn [21 POLL]

512-byte transfers

USB Analyzer

- Opening the transactions gives more insight

HS	269957	1:51.484.936	512 B	05	01	IN txn [21 POLL]
HS	269962	1:51.484.971	512 B	05	01	IN txn [33 POLL]
HS	269967	1:51.485.059	83 ns			[1 SOF]
HS	269968	1:51.485.020	512 B	05	01	IN txn [25 POLL]
HS	269969	1:51.485.020	25.2 us	05	01	[25 IN-NAK]
HS	269970	1:51.485.061	3 B	05	01	IN packet
HS	269971	1:51.485.061	515 B	05	01	DATA1 packet
HS	269972	1:51.485.070	1 B	05	01	ACK packet
HS	269973	1:51.485.075	512 B	05	01	IN txn [34 POLL]
HS	269974	1:51.485.075	34.9 us	05	01	[34 IN-NAK]
HS	269975	1:51.485.110	3 B	05	01	IN packet
HS	269976	1:51.485.110	515 B	05	01	DATA0 packet
HS	269977	1:51.485.119	1 B	05	01	ACK packet
HS	269978	1:51.485.124	512 B	05	01	IN txn [34 POLL]
HS	269983	1:51.485.184	83 ns			[1 SOF]
HS	269984	1:51.485.186	512 B	05	01	IN txn [19 POLL]
HS	269989	1:51.485.219	512 B	05	01	IN txn [34 POLL]
HS	269994	1:51.485.309	83 ns			[1 SOF]
HS	269995	1:51.485.268	512 B	05	01	IN txn [27 POLL]
HS	270000	1:51.485.324	512 B	05	01	IN txn [34 POLL]

Host Requests data

Device sends NAKs for 41 us. (device latency)

5 us between ACK and next request (host latency)

USB Analyzer

- Observations
  - Certainly the 41us of NAK time is **less than ideal**.
  - Don't be fooled by the displayed 5us between transactions.
    - In this case the host is spinning on IN-NAK
  - The bus scheduler can **adapt** to the actual time between packets.
    - Number of IN-NAKs will **go down**
    - Time will stay the **same**.
    - Don't count NAKs; look at times!

Transfer Sizes

- What changes with **multi-transaction** transfers?
  - Depends on the UDC hardware.
  - Many UDC controllers use **DMA** at the **Transfer-level.**
    - One **DMA transfer** per USB transfer.
    - Minimizing the number of DMA transfers will decrease DMA overhead.
    - Decrease the number of transfers by **increasing the transfer size**.
  - Fewer trips to user-space!

Transfer Sizes

- Increased transfer size
  - Limited by hardware/DMA/Driver
  - **64kB** seems to work well
    - Performance increases with transfer size up to 64k and plateaus in testing.
  - Performance with 64kB transfers:
    - BeagleBone Black: **211 Mbit/sec**
    - Intel E680 Board: **305 Mbit/sec**

USB Analyzer – Large Transfers

Example: Transfer size = 2047 (512 * 3 + 511)

353613	0:06.625.332	512 B	03	01	IN txn
353617	0:06.625.343	511 B	03	01	IN txn [7 POLL]
353622	0:06.625.363	512 B	03	01	IN txn [39 POLL]
353627	0:06.625.414	512 B	03	01	IN txn [7 POLL]
353632	0:06.625.432	512 B	03	01	IN txn [7 POLL]
353637	0:06.625.456	66 ns			[1 SOF]
353638	0:06.625.457	511 B	03	01	IN txn
353642	0:06.625.471	512 B	03	01	IN txn [39 POLL]
353647	0:06.625.521	512 B	03	01	IN txn [6 POLL]
353652	0:06.625.537	512 B	03	01	IN txn [6 POLL]
353657	0:06.625.554	511 B	03	01	IN txn [6 POLL]

Single Transfer
Transfers end with the 511-byte transaction

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USB Analyzer – Large Transfers

Same Transfer, but with first two transactions open

353617	0:06.625.343	511 B	03	01	IN txn [7 POLL]
353622	0:06.625.363	512 B	03	01	IN txn [39 POLL]
353623	0:06.625.363	39.4 us	03	01	[39 IN-NAK]
353624	0:06.625.404	3 B	03	01	IN packet
353625	0:06.625.404	515 B	03	01	DATA0 packet
353626	0:06.625.413	1 B	03	01	ACK packet
353627	0:06.625.414	512 B	03	01	IN txn [7 POLL]
353628	0:06.625.414	6.61 us	03	01	[7 IN-NAK]
353629	0:06.625.421	3 B	03	01	IN packet
353630	0:06.625.422	515 B	03	01	DATA1 packet
353631	0:06.625.431	1 B	03	01	ACK packet
353632	0:06.625.432	512 B	03	01	IN txn [7 POLL]
353637	0:06.625.456	66 ns			[1 SOF]
353638	0:06.625.457	511 B	03	01	IN txn
353642	0:06.625.471	512 B	03	01	IN txn [39 POLL]
353683	0:06.625.705	83 ns			[1 SOF]

First Transaction

39.4 us lost between transfers

Only 6.6 us lost between transactions

Single Transfer

A significant improvement over losing ~40 us between each transaction!

Large Transfers

- What about Full Speed?
  - PIC32MX tops out around **8.6 Mbit/sec**.
    - 64 kB transfer
  - Using the **asynchronous** API, performance improvement with transfer size is not as dramatic:
    - **8.2 Mbit/sec** with 64-byte transfers

Large Transfers

- Limitations
  - USB is a **message-based** protocol.
    - It's **convenient** to put one logical piece of data into its own transfer.
    - Packing multiple logical pieces of data into one large buffer **loses some of the benefit** of the USB protocol.
    - A **necessary trade-off** if performance is desired.
  - Queuing of messages can cause **increased latency** (marginal).

Other Considerations

- User space vs Kernel space
  - The above examples use the kernel's **Functionfs** interface on the **device** side.
    - Functionfs takes **transfers** from a user space process synchronously.
      - Synchronous –> delay between transfers
      - Larger transfers –> fewer trips to user space
    - It would be better to **queue** packets on the **device side** inside the kernel.
      - Queuing can happen even when the hardware is busy.
      - Currently requires a **custom driver**.

Custom Driver

- Driver details
  - Custom Driver has a queue of **32 transfers**
  - Device node at `/dev/user-gadget`
- Performance
  - BeagleBone Black:
    - **227** Mbit/sec, ~**7.6**% better than functionfs
  - EG20T:
    - **328** Mbit/sec, , ~**7.5**% better

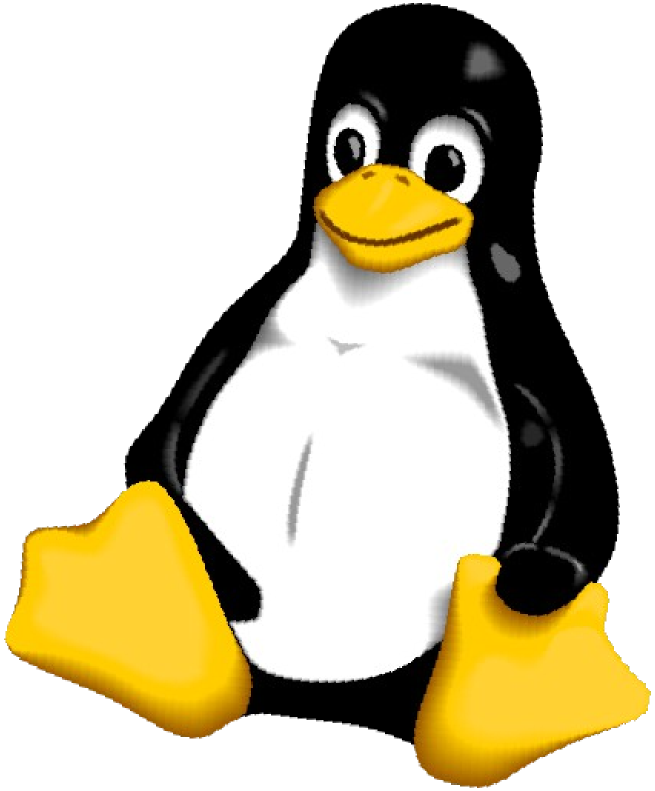
Out Transfers

- One might expect **OUT** transfers to behave similarly to IN transfers.
- On musb, they **do not**
  - musb: Max throughput of **65.5 Mbit/sec**
    - Same for **sync and async**
    - 64 kB transfers
  - For data **received**, a DMA transfer is done for **every USB Transaction**.
    - Overhead is high
    - Large transfers don't help :(

Out Transfers

- On EG20T
  - Max throughput of **255 Mbit/sec**
    - 64 kB transfers
  - Still slower than IN transfers
  - Throughput scales with transfer size.

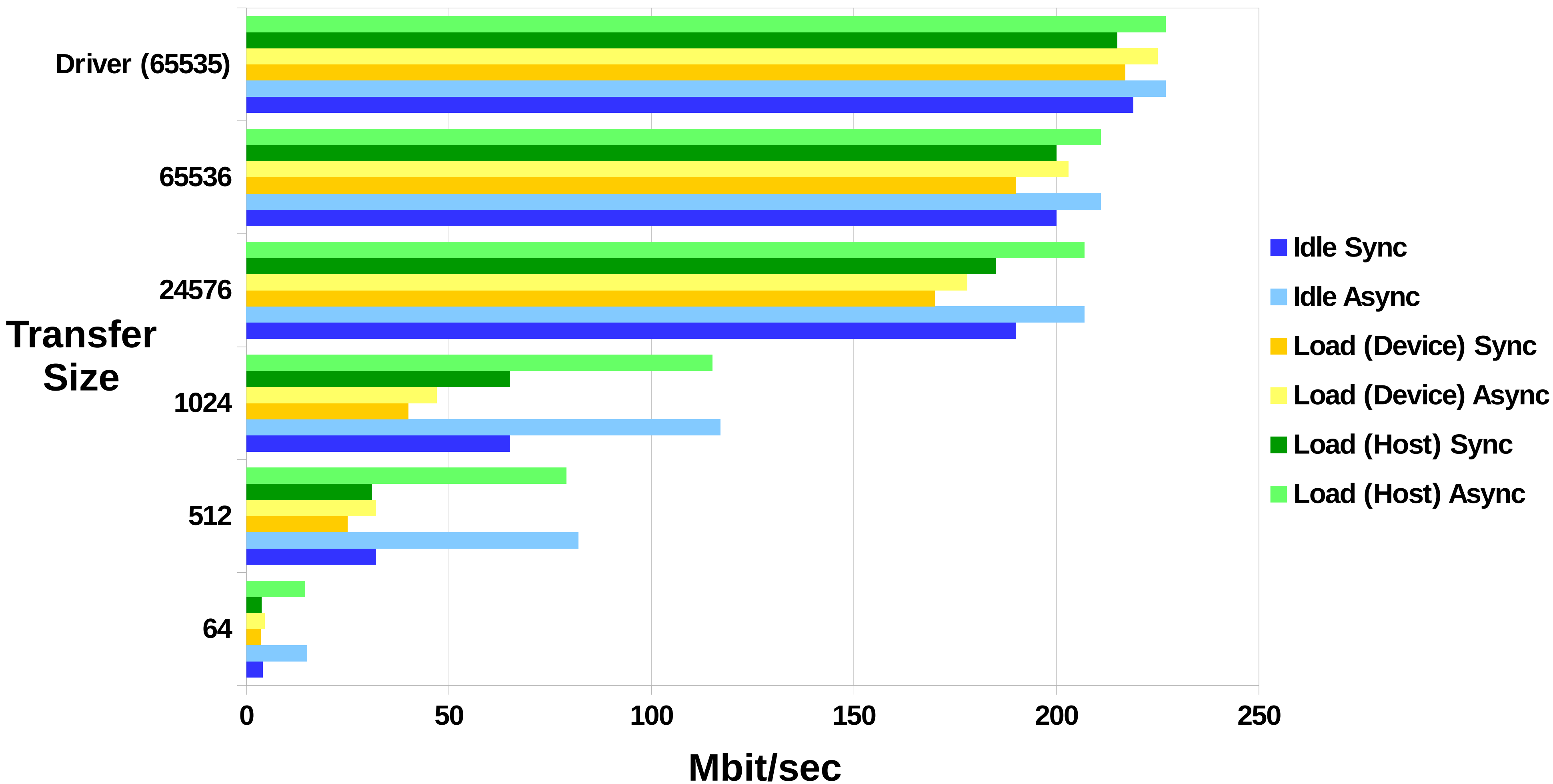
Results



Test Methodology

- Test with the **synchronous** and **asynchronous** libusb API's
- Test **idle** and under **load**
  - **Device** load (musb):
    - `stress -c 1 -m 1`
  - **Device** load (EG20T):
    - `stress -c 2 -m 2`
    - *Host machine has one hyperthreaded core*
  - **Host** load:
    - `stress -c 4 -m 4`
    - *Host machine has 4 cores*

musb Results (IN Transactions)



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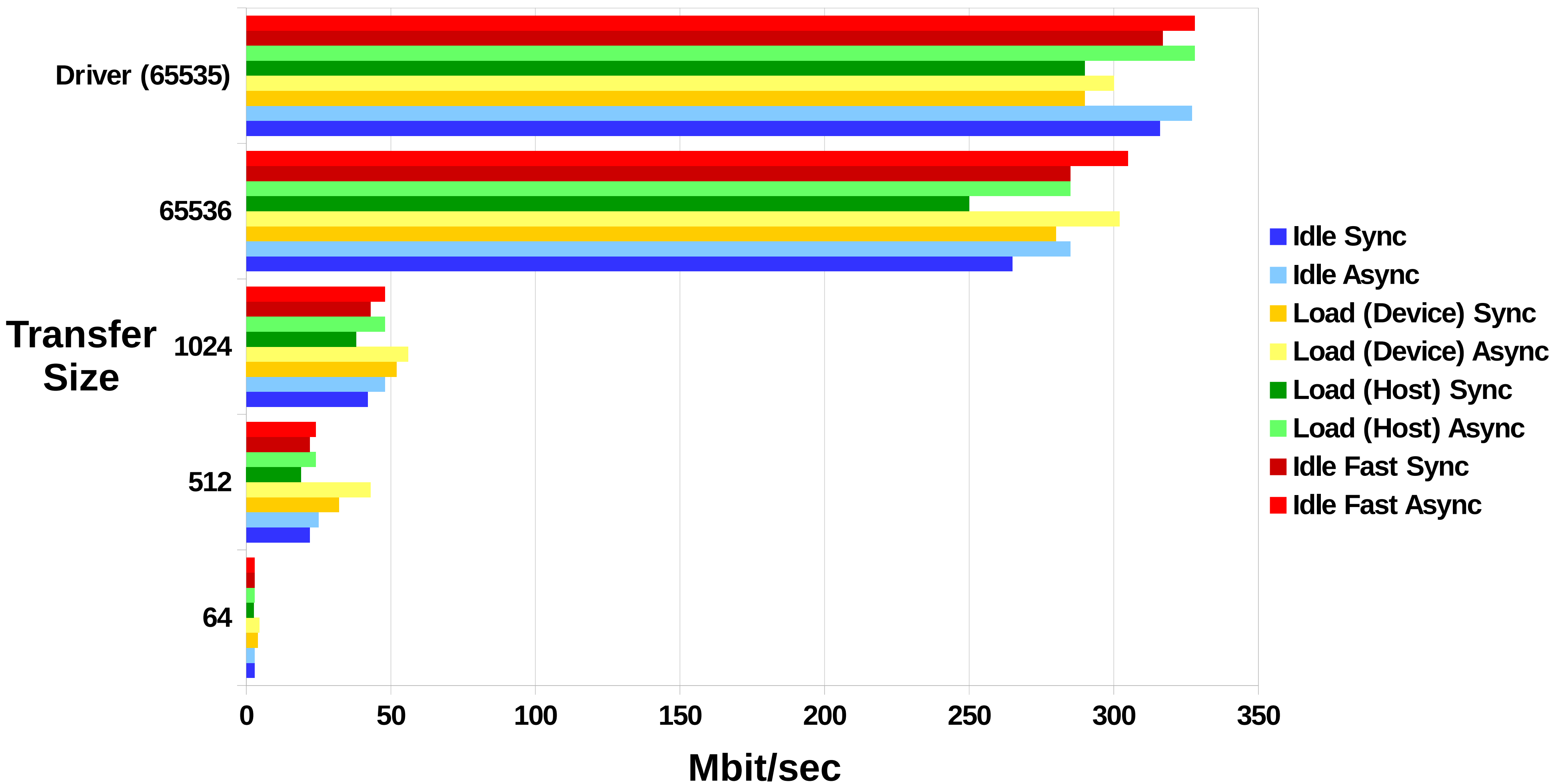
EG20T Results (IN Transactions)



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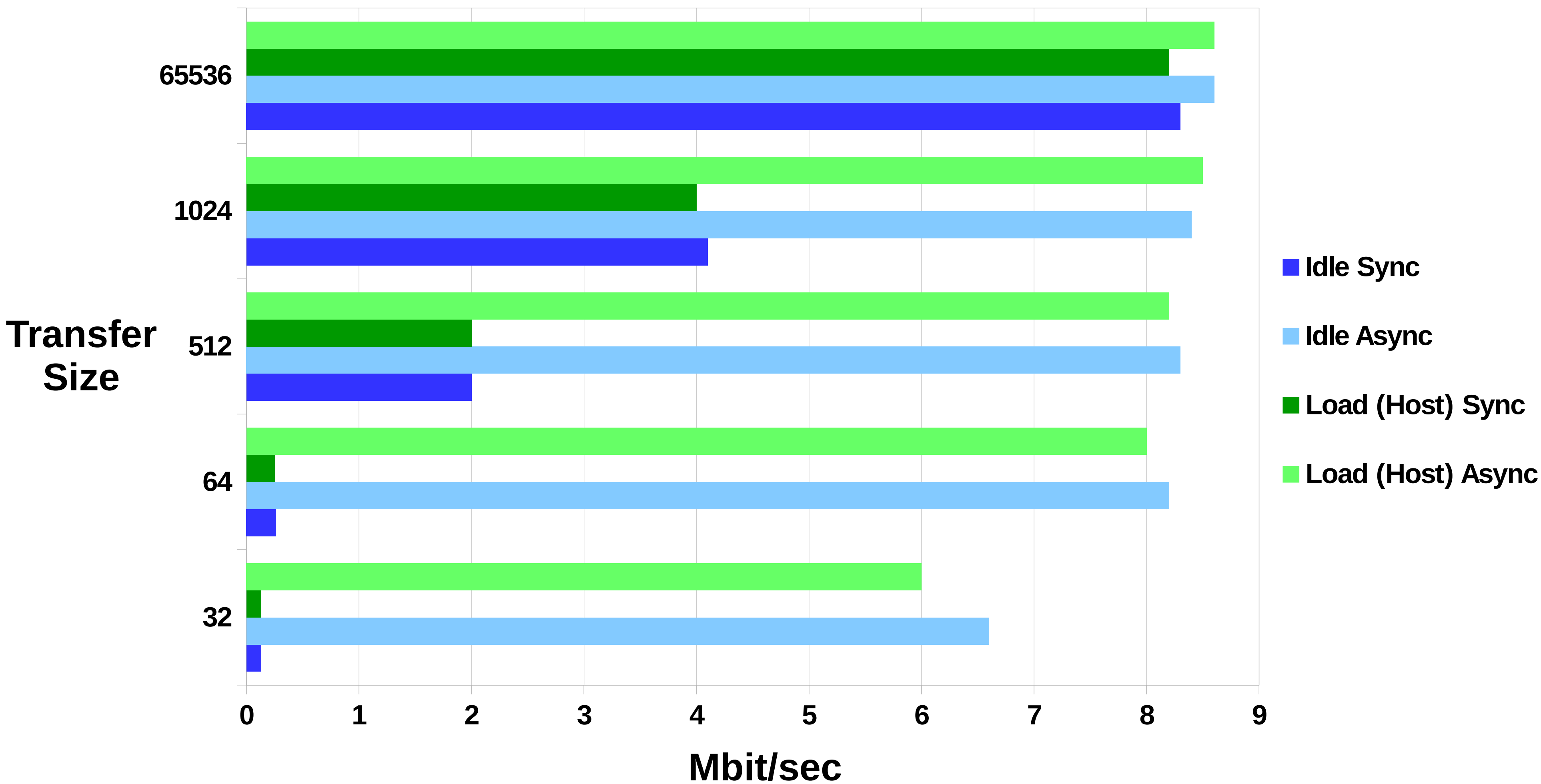
Results

- Warning:
  - Comparisons between controllers should be considered **cautiously**.
    - Plenty of **differences** between boards/platforms.
    - Different **CPU speeds** affect performance tremendously.
      - One Dual core, one single core
    - We know what they say about benchmarks.
    - Use the data to compare effects **within** a controller type

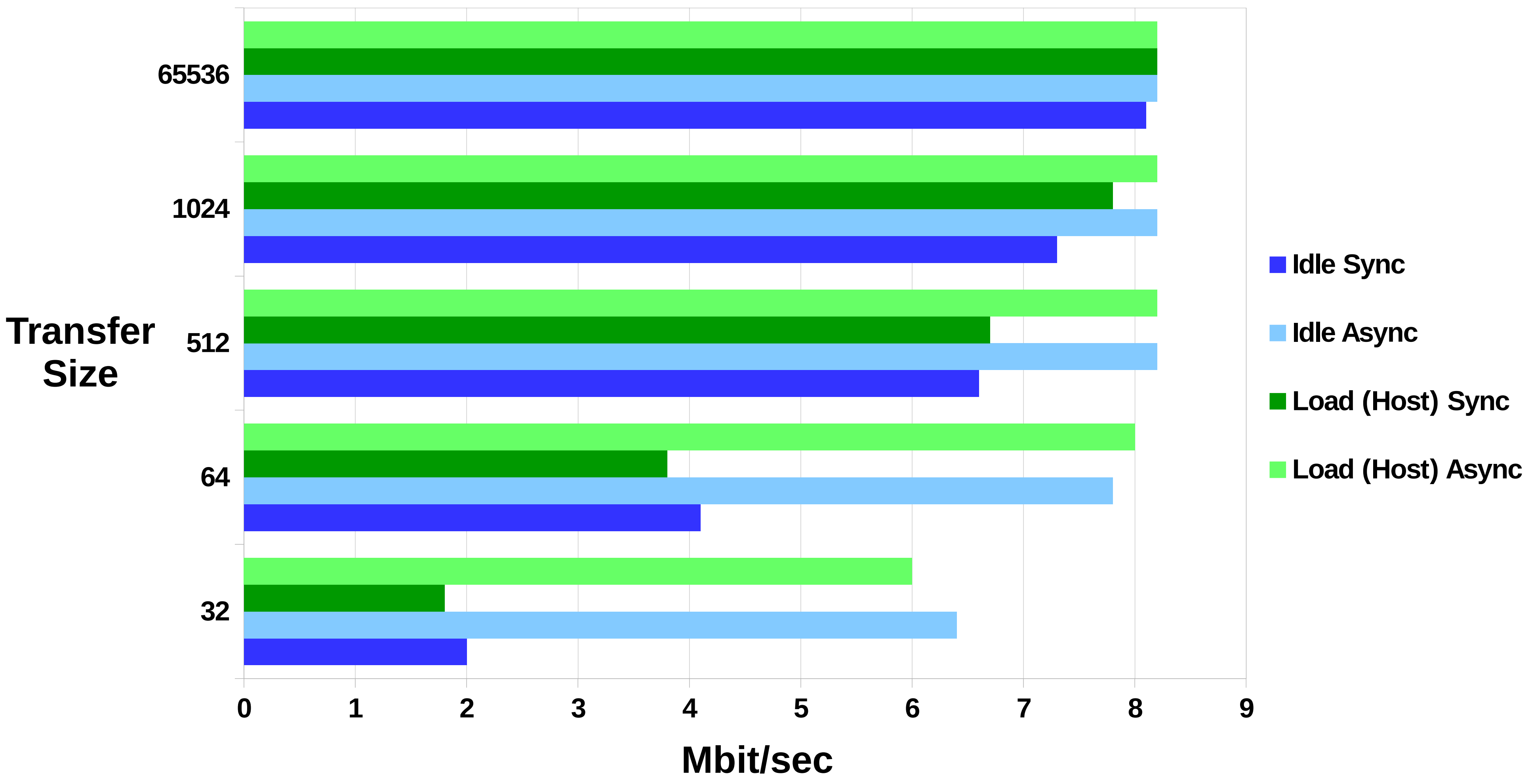
Results

- musb/EG20T (Input) Analysis
  - **Larger transfer** size is **much** better
  - Sync/Async affects **smaller transfers** more than larger transfers.
    - Less time proportionally lost between transfers
  - Host Load doesn't make much difference
  - Device Load makes **more** difference
    - Data is sourced from user space

PIC32MX Results (IN Transactions)



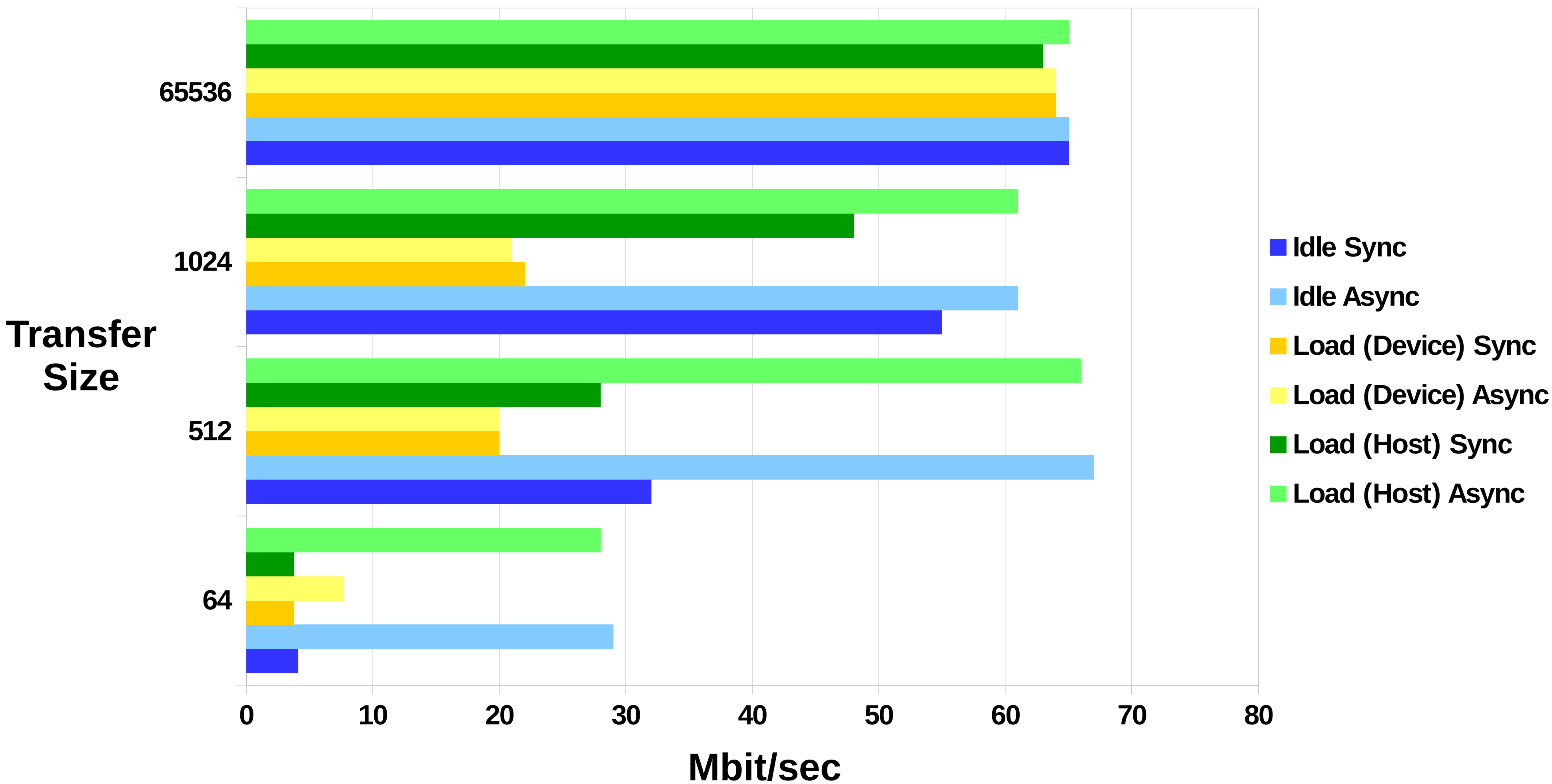
PIC32MX Results (IN TXN **with hub**)



Results

- PIC32MX (Input) Analysis
  - **Larger transfer** sizes don't help as much for sync as they do for async.
  - Addition of a **hub** has a surprising affect
    - Analyzer shows **more frequent** IN tokens when connected through a hub.
    - Synchronous transfers are **faster**
    - Asynchronous transfers **slightly slower**

musb Results (OUT Transactions)



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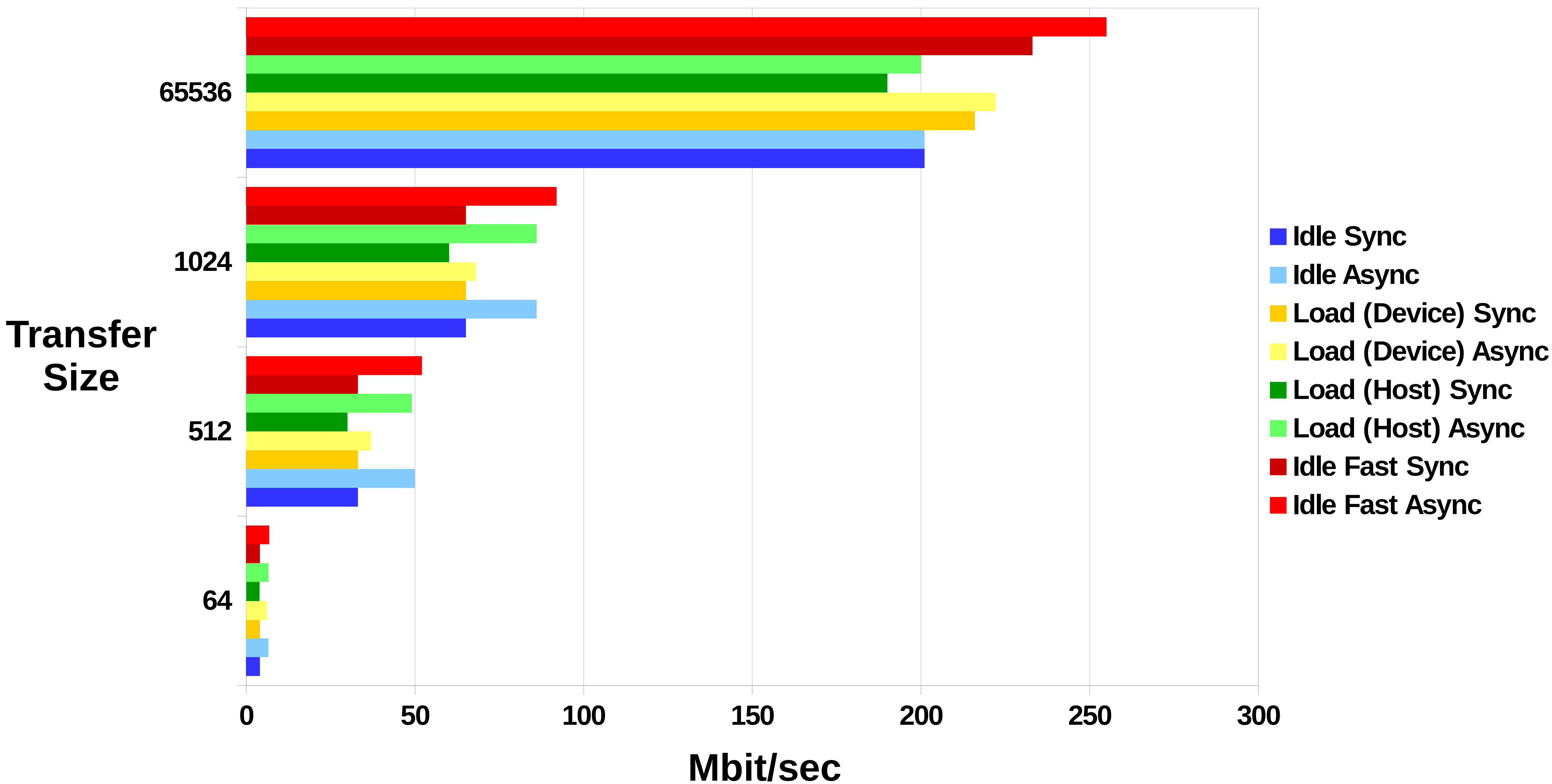
EG20T Results (OUT Transactions)



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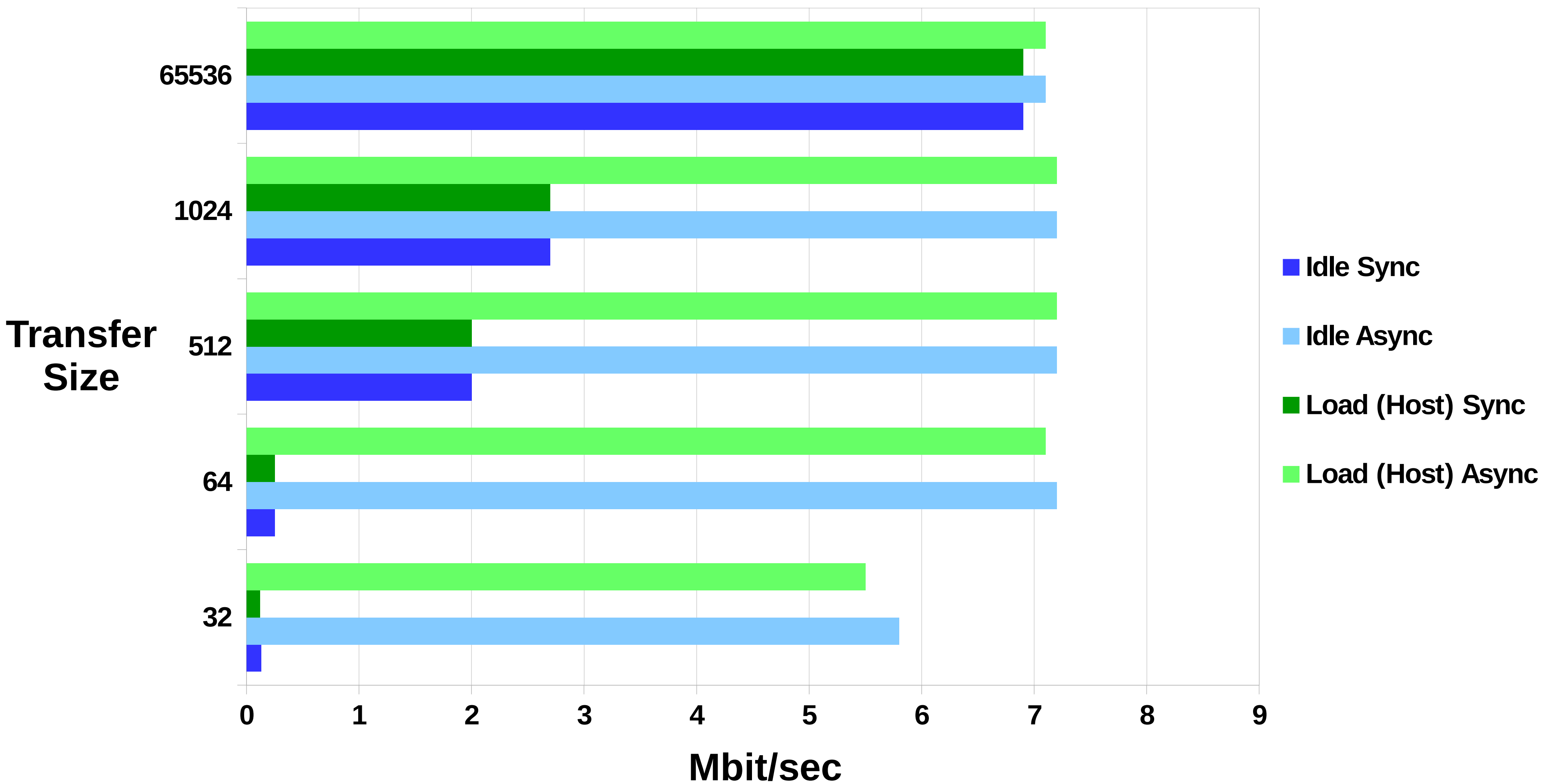
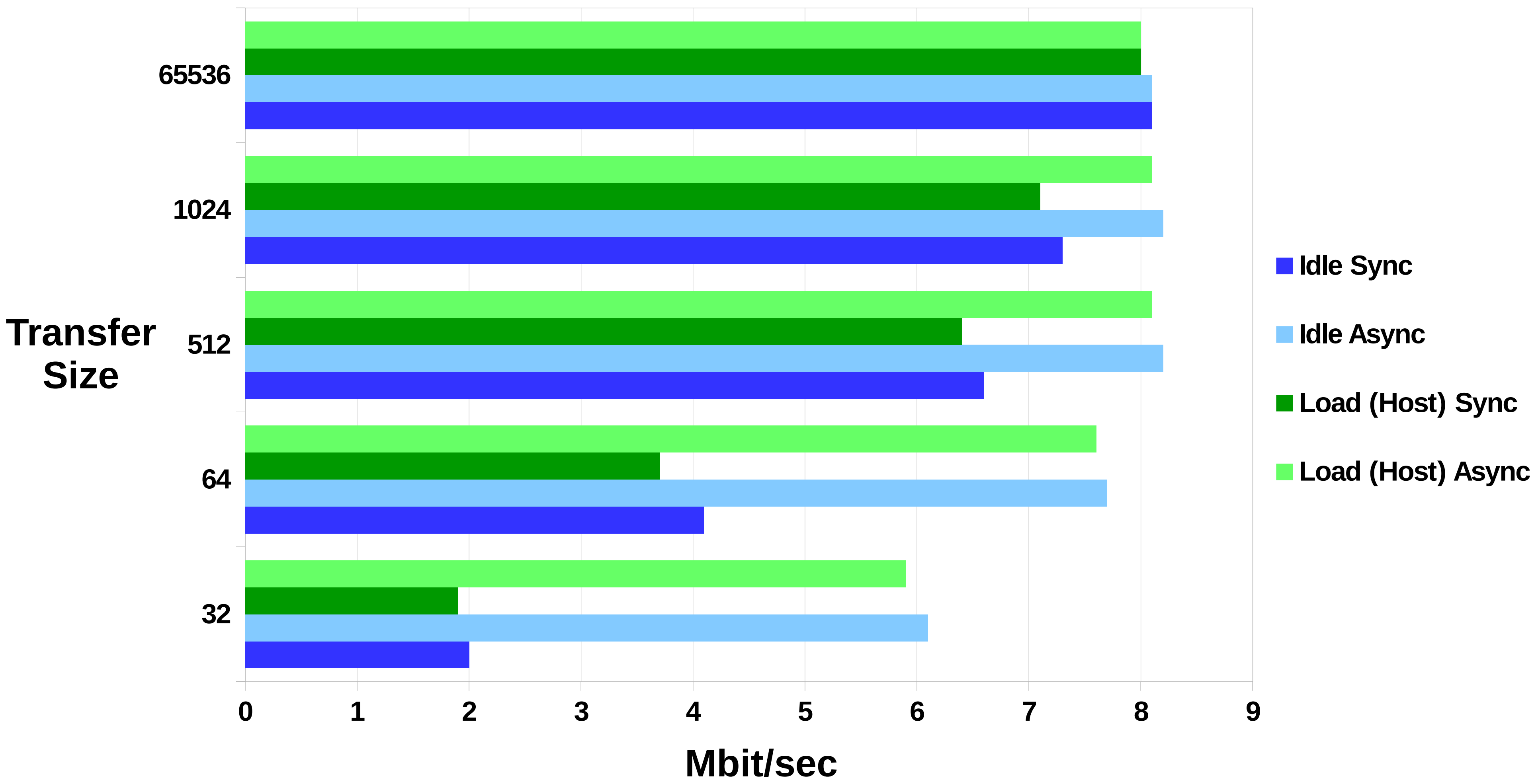
Results

- musb/EG20T (OUT) Analysis
  - musb does one DMA transfer **per USB transaction.**
  - Performance **tops out** with 512-byte transfers
    - Endpoint size is 512.
  - EG20T OUT performance **scales similarly to IN** performance.
  - Hub numbers are similar but **slightly slower** (see spreadsheet)

PIC32MX Results (OUT Transactions)



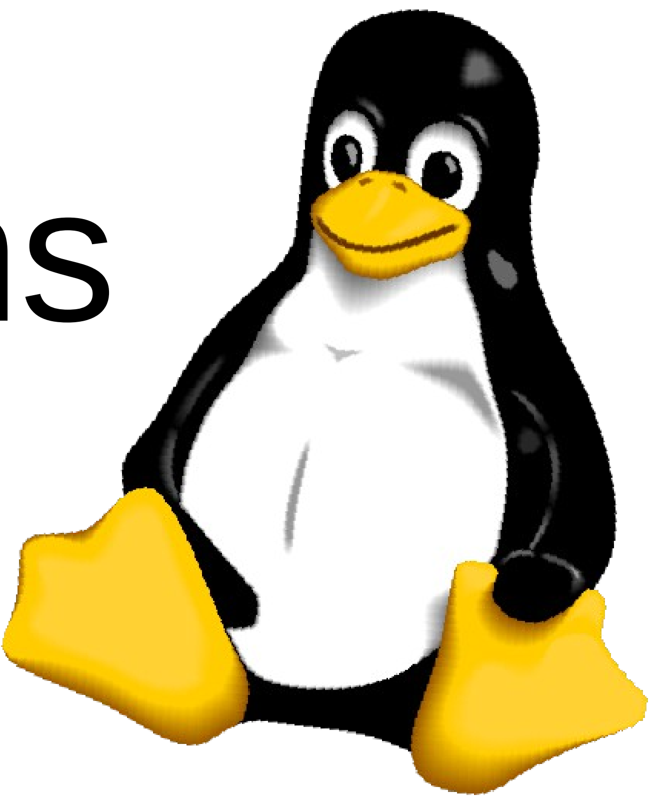
PIC32MX Results (OUT TXN **with hub**)



Results

- PIC32MX (Output) Analysis
  - OUT transfers are affected by the hub the same way IN transactions are
  - Speed is **comparable** to IN transfers

Further Optimizations



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Isochronous Endpoints

- Features
  - **Un-acknowledged**, non-guaranteed
  - Bandwidth reserved
  - Up to 3x1024 bytes per 125us microframe
    - **3072** bytes/frame: **196 Mbit/sec** per endpoint
- Issues
  - Requires AlternateSetting
    - Not supported by functionfs
  - Bandwidth must be available

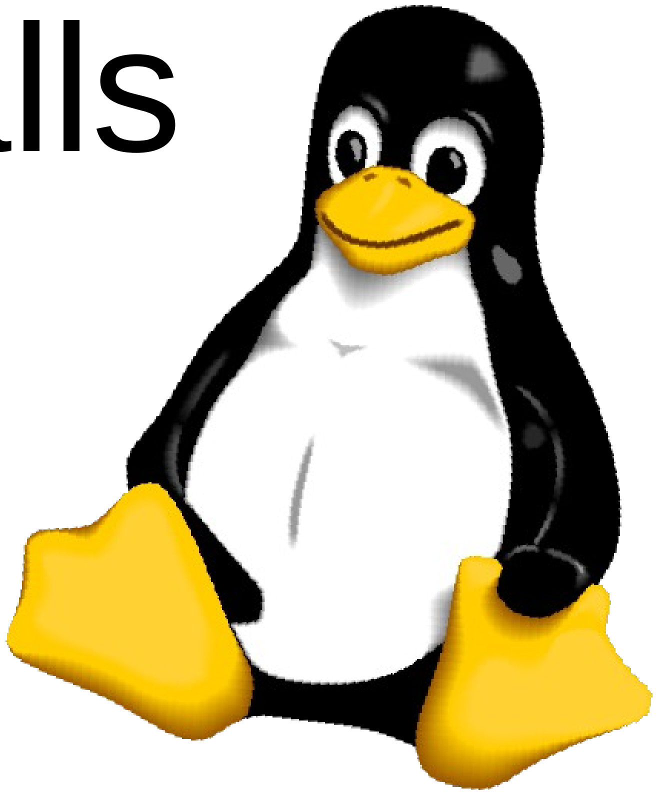
Multiple Endpoints

- Using **multiple bulk endpoints** can increase performance.
  - All endpoints and devices share **bus** time
  - If bottleneck is DMA, extra concurrency could increase performance.
  - More **complex** to manage.
  - Depends also on **host scheduling**.

High-Bandwidth Interrupt

- High-speed Interrupt endpoints at > 1024 bytes
  - Can go as high as **3072**
  - Reserved Bandwidth
  - Acknowledged
  - **AlternateSetting** required
  - Bus bandwidth **must be available**
    - Device will **fail to enumerate** or change AlternateSetting if bandwidth is not available.

Common Pitfalls



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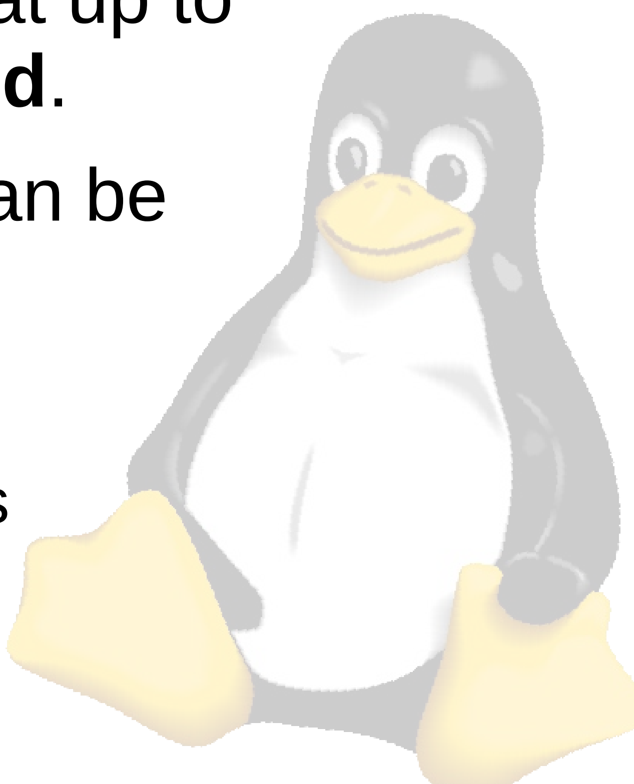
Common Pitfalls

- HID
  - Based on **Interrupt Transfers**.
  - Host will poll interrupt endpoints at up to once per **1ms frame** at **full speed**.
  - Interrupt transfers at full speed can be up to **64 bytes** in length.
  - Simple math is 64,000 bytes/sec
    - Good enough for many applications
  - Except....



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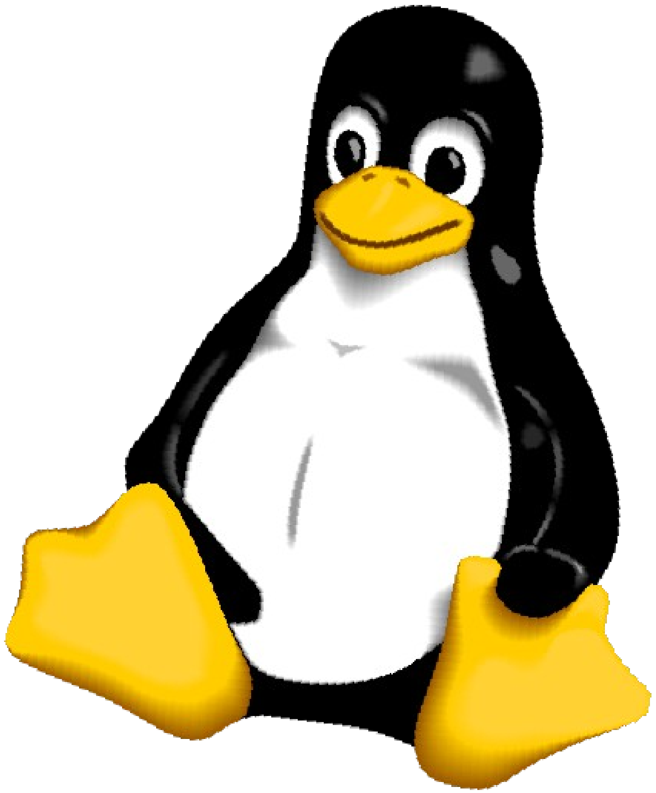
Common Pitfalls

- HID
  - … Except you don't always get it! **Many hosts don't actually poll you that often!**
    - **2-4 frames** is much more realistic (sometimes worse!)
    - Some write **synchronous** protocols with HID
      - Those are even slower!
        - 2-4 frames for data, 2-4 frames for acknowledgement!
          - **8 kB/sec** in this case
  - Use **Bulk/Isoc** endpoints!
    - Use **libusb** on the host side

Common Pitfalls

- Serial Gadget
  - The `f_serial` gadget interface creates /dev/ttyGSn nodes.
    - Data is written/read to/from these nodes from the **gadget/device** side.
    - Since the data goes through the **tty** framework, it is broken into **small transfers**.
    - Performance is **suboptimal**, but ease of use is high.

Tracepoint Analysis



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Tracepoints

- The kernel provides a **tracing** mechanism
  - Tracepoints are placed in source code
  - **Enabled/disabled** at runtime
  - Tracepoints can log **data**
  - **`trace-cmd`** utility to log data
  - **`kernelshark`** GUI to view/analyze it
  - Useful for finding latencies

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Tracepoints

- Available Tracers
  - Additional tracers need to be enabled in `menuconfig`
    - Log every kernel function
    - Log call stack
    - Trace system calls
    - Scheduling latency
    - Others...

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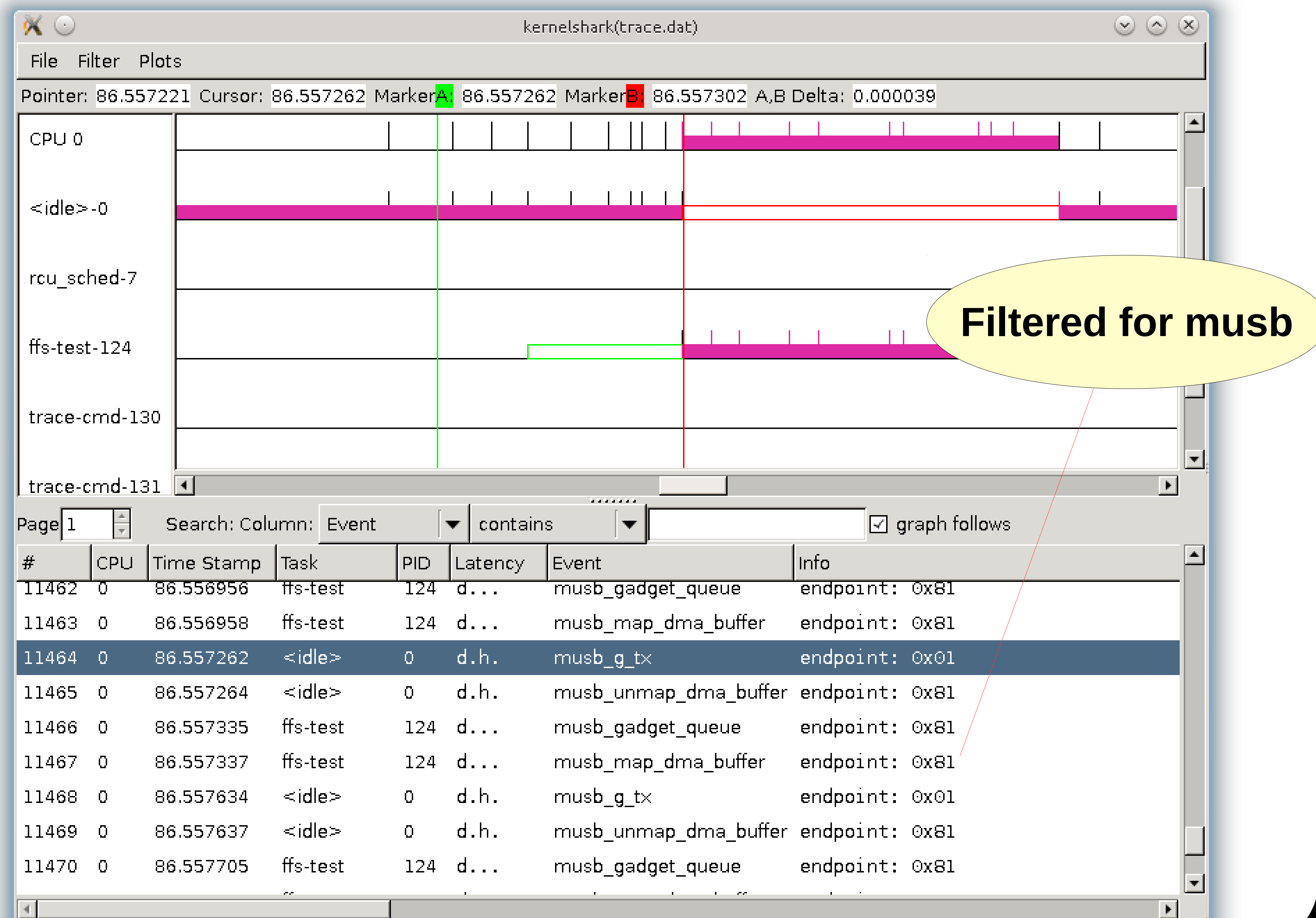
KernelShark

- **GUI** for trace analysis
  - Graphically show tracepoints
    - Per-CPU
    - Per-process
  - Show tracepoint data
  - Complex **filtering**
    - By process, CPU, event type or name

KernelShark



Tracepoints

- musb driver was **modified** to add tracepoints
  - Declare tracepoints:
    - musb-trace.h
  - Call tracepoint functions (with data):
    - musb_gadget.c
    - musbhsdma.c

Tracepoints

- Results
  - Results show the **latency** involved in the **context switch**.
    - Along with DMA overhead, another reason to use large transfers.

Lessons Learned

- Gadget interface is Fragile
- Functionfs doesn't support AltSettings
  - No Isochronous endpoints
  - No high-bandwidth Interrupt endpoints
- Hubs
  - Can have strange effects
  - Some good, some bad.

Signal11

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